Exploring the Sun and its effects on the Earth's atmosphere and physical environment...

HIGH ALTITUDE OBSERVATORY

MHD Simulations of Sunspot Structure

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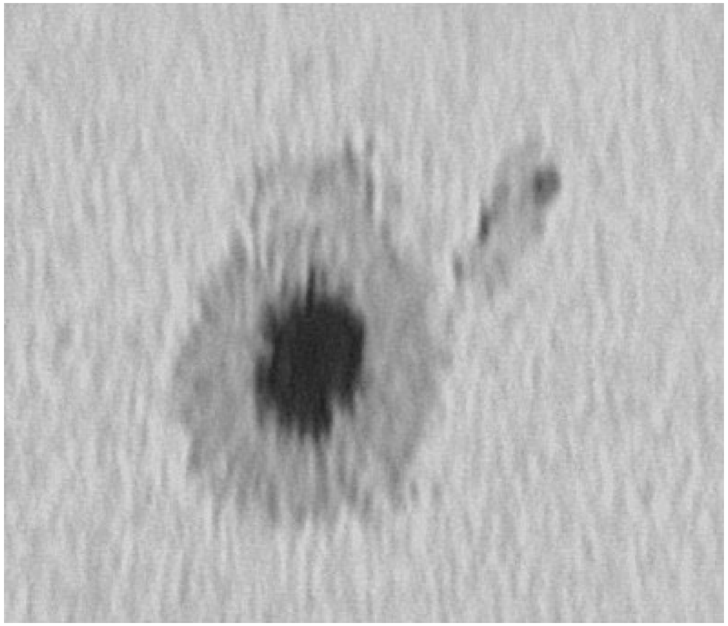
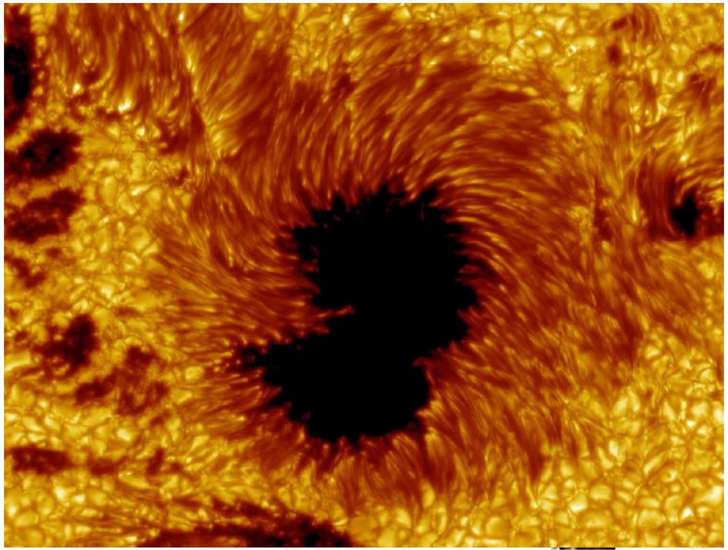
The problem

- No fundamental progress in our understanding of sunspots for decades
- Why?
  - Insufficient resolution of fine structure
  - No information about subsurface structure
  - Insufficient computational power for simulations from first principles
- Recently progress on all 3 fronts:
  - AO, images selection & reconstruction, spectropolarimetry from space (Hinode)
  - Local helioseimology
  - Massively parallel computers





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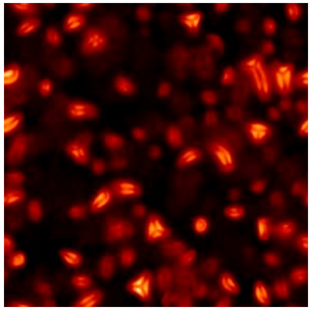
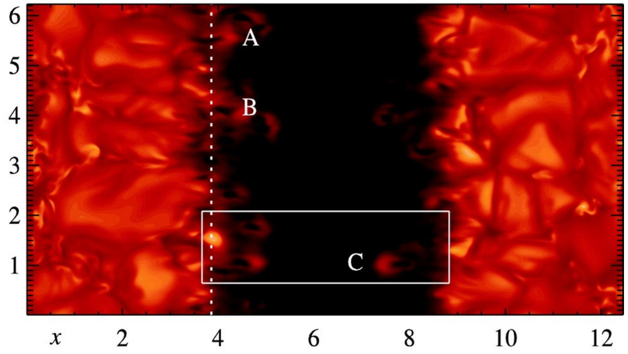
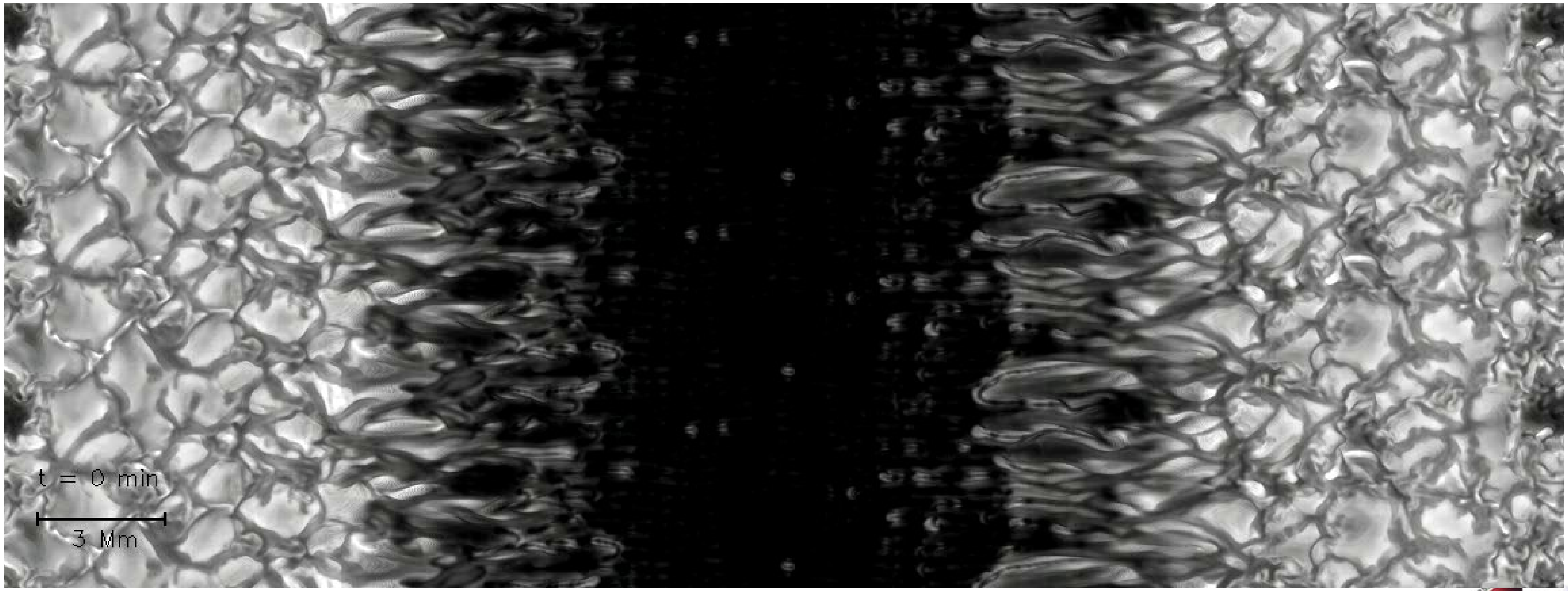
Recent progress



Schüssler & Vögler (2006)



Heinemann et al. (2007)



Rempel et al. (2009)

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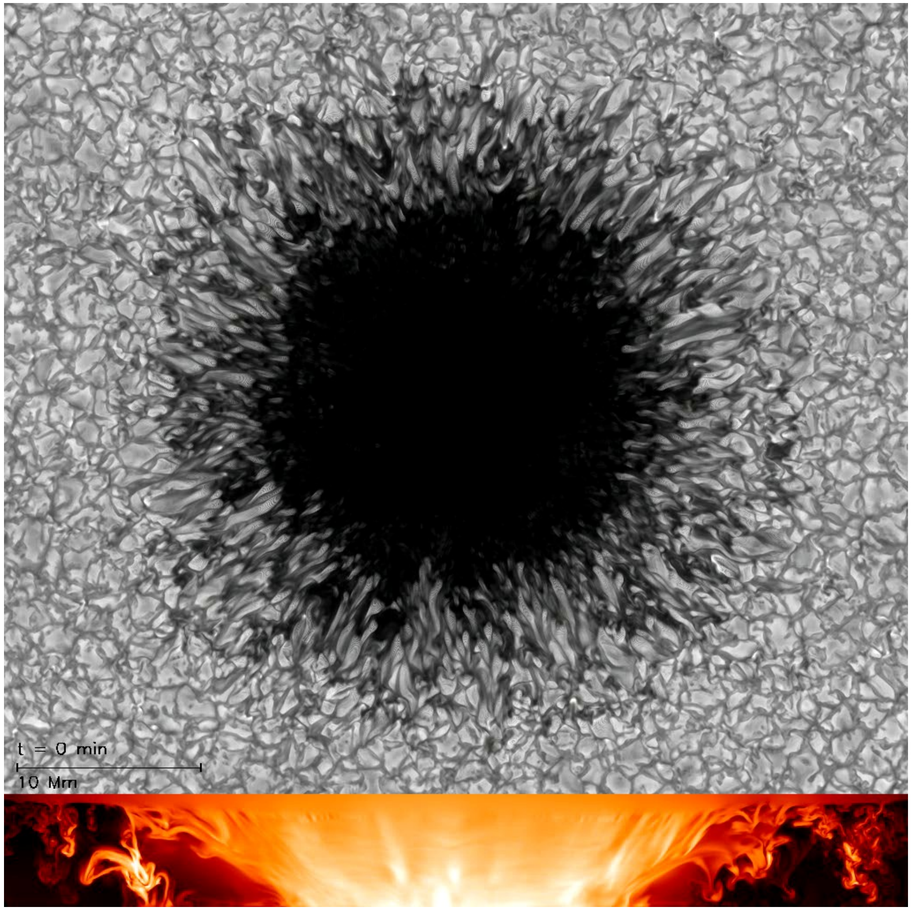
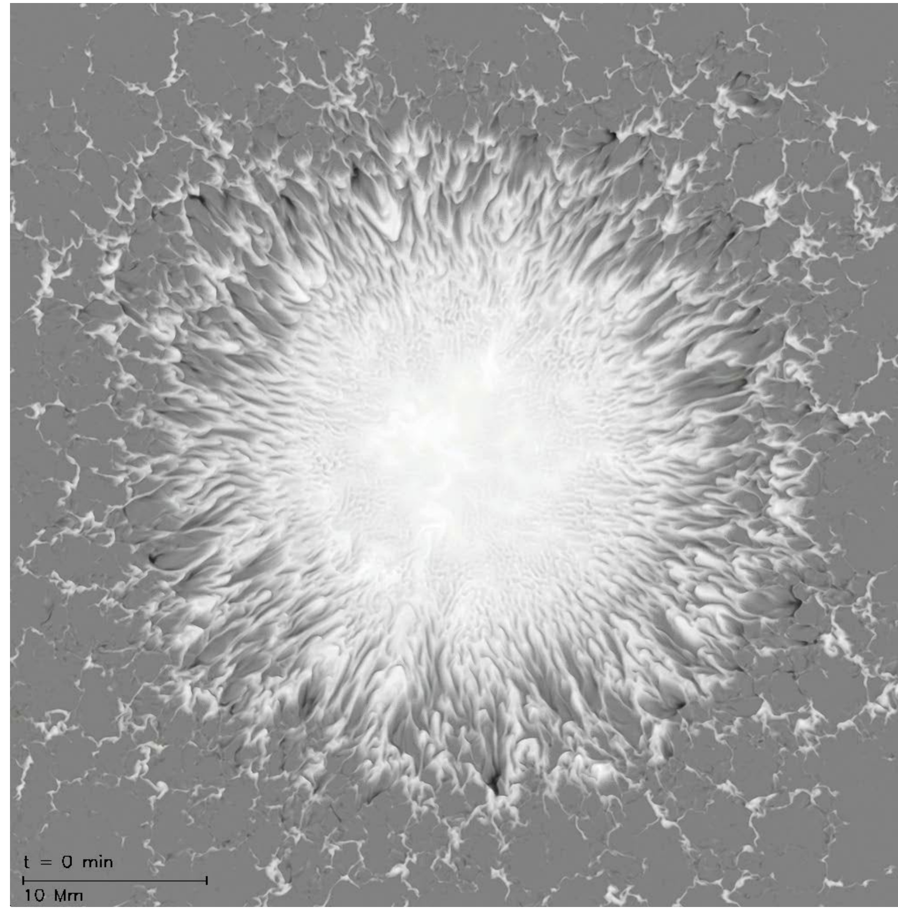
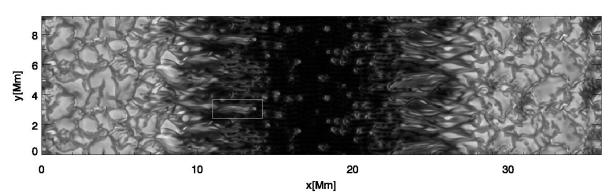
Last 4 months





1.8×10^{22} Mx sunspot in 50x50x6 Mm domain



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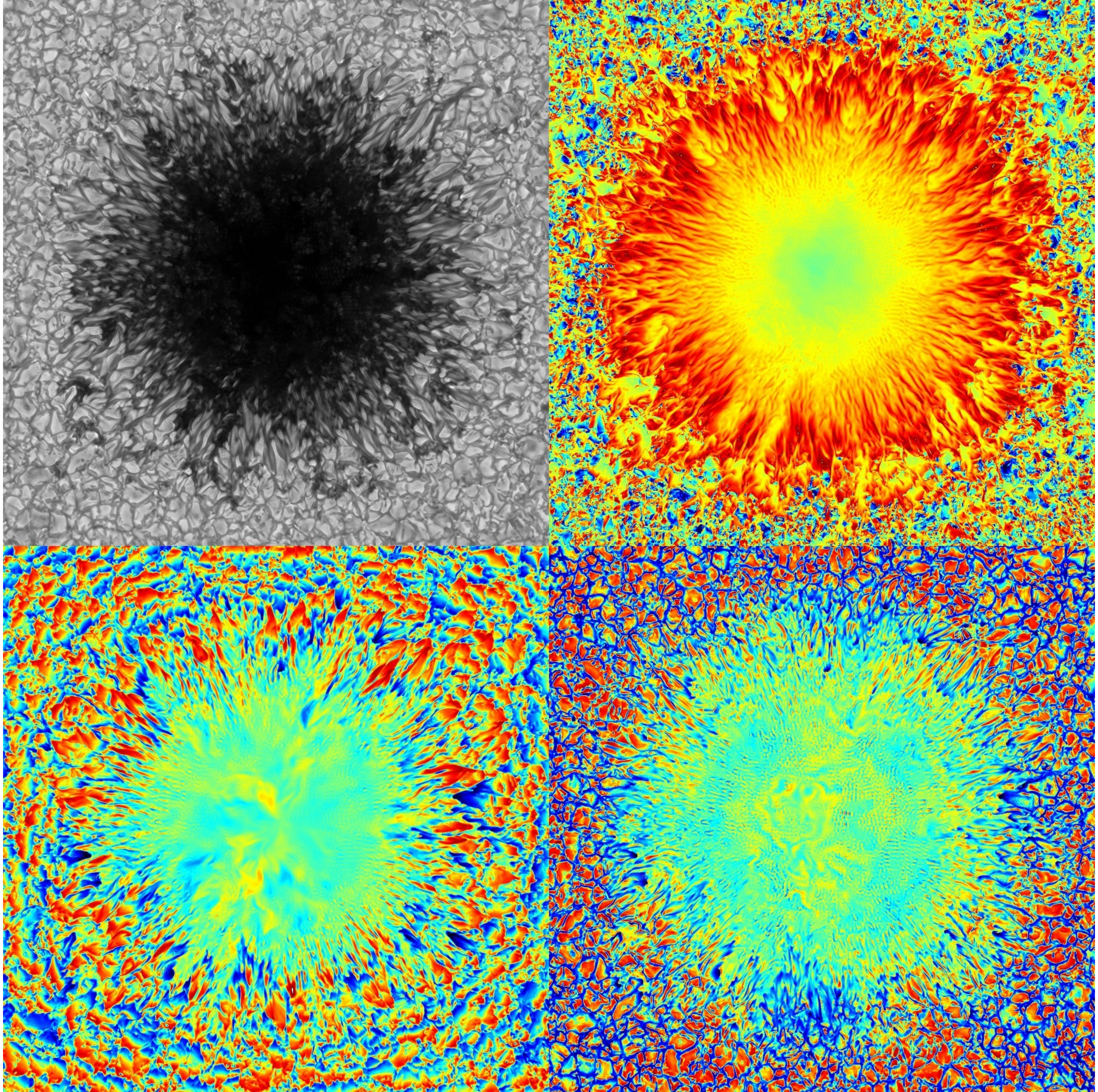
Intensity

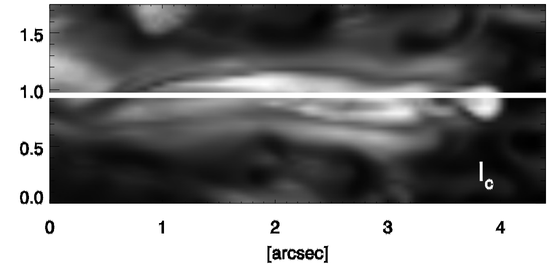
Inclination

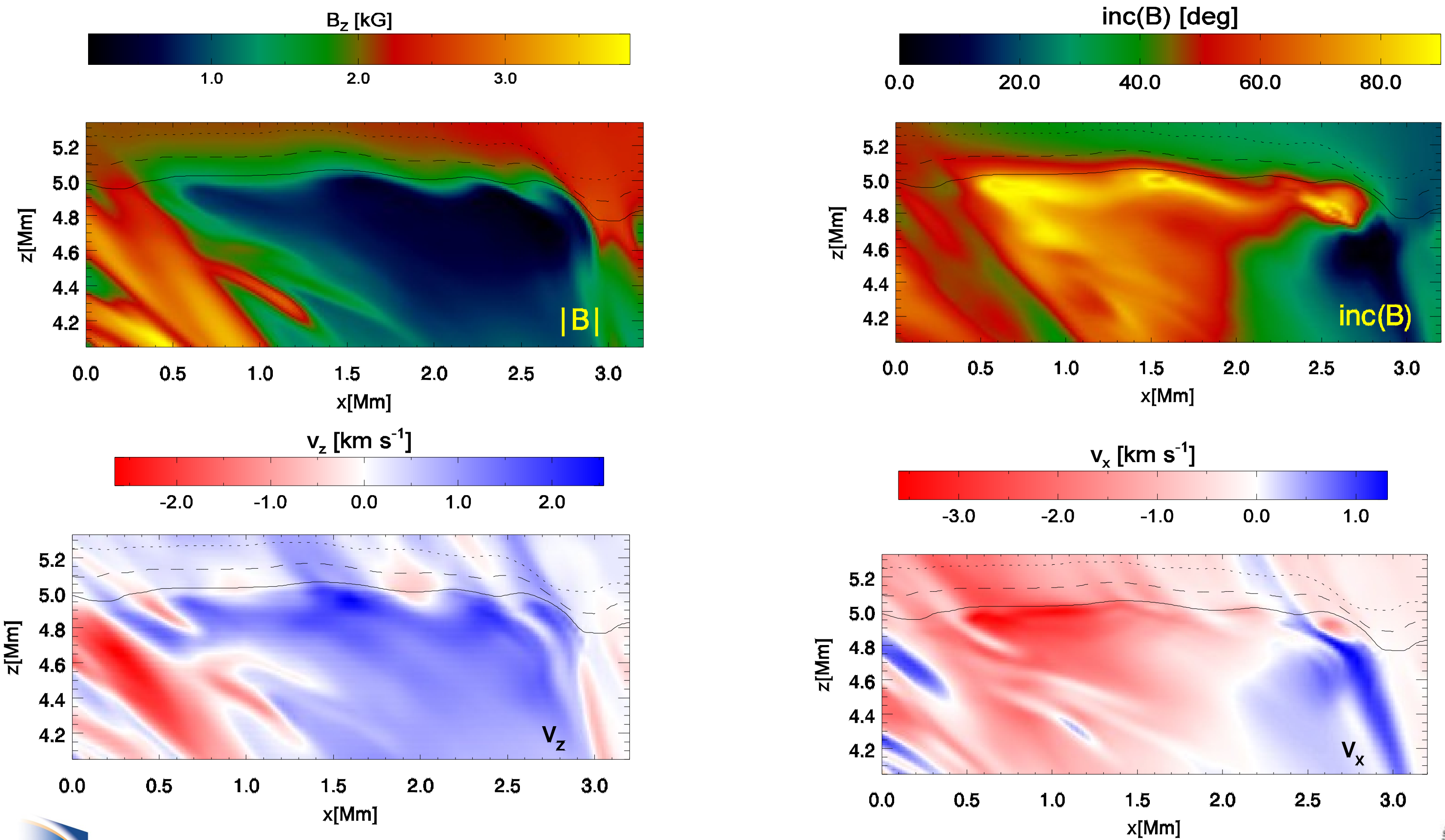


Vr

Vz

Vertical cuts along the filament





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Results

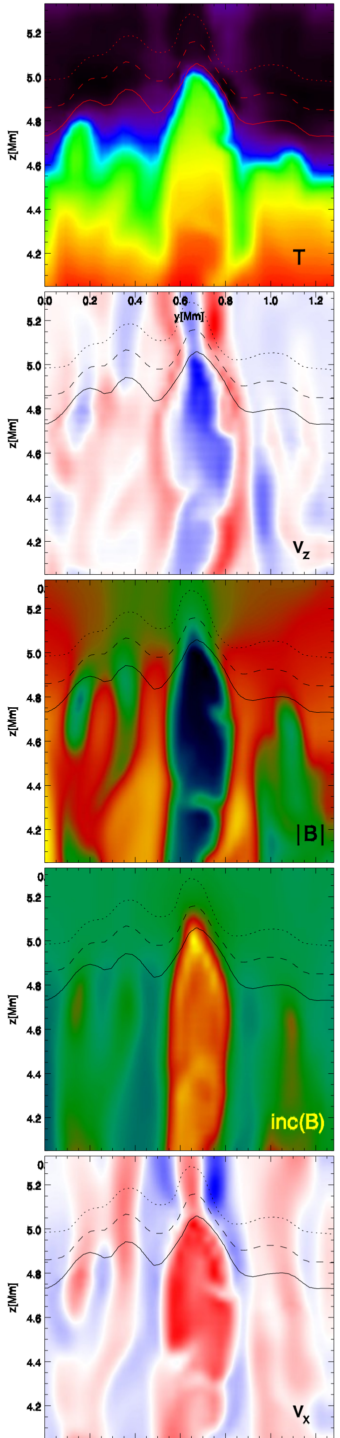
- Separated filaments with observed properties
  - Filaments with dark cores
  - Almost horizontal field, horizontal flow of ~ 2 - 3 km/s
  - Important: horizontal flow in magnetized region (required to explain observed circular polarisation)
- No dense penumbra (yet)
  - Interface umbra/penumbra
  - Evershed flow on average too weak ~2 - 3 km/s, peak flows ~9 km/s
- Common magneto-convective origin of umbral dots and penumbral filaments
  - Overturning convection central element
  - Umbral dots: almost field free upflow plumes
  - Penumbral filaments: presence of horizontal field leads to preferred direction

Gaps or flux tubes?

- Overall structure looks like 'gaps', but
  - no intrusion of field free plasma from 'outside'
  - 'gaps' open within strong field due to magneto- convection
  - 'gaps' filled with mainly horizontal field
- Photospheric appearance 'tube'-like, but
  - description of entire structure as tube not very meaningful (variation over cross section ~ variation along axis)
- Basic agreement with conclusions from Hinode observations

Not yet settled questions

- Observational evidence for overturning convection?
  - Ichimoto et al (2007)
    - ‘twisting’ motions in filaments
  - Rimmele (2008); Zakharov et al. (2008); Bharti et al. (2007):
    - Direct observation of overturning motions
  - More evidence in umbral dots?
  - Several other studies looked for signature, but couldn’t detect it!
- Need improvement (resolution) of simulations!
  - Are flows hidden from visible layers?
- More observations needed?
  - High resolution observations of deep photospheric lines with narrow contribution function
  - 50cm telescope likely not enough for that



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Not yet settled questions

- Evershed flow
  - Preferred outflow along filaments, but amplitude too weak
- Role for energy transport?
  - Energy primarily transported by overturning motions
    - 1-2Mm deep reaching upflows ~1km/s
  - Role of horizontal flow potentially underestimated
- Issue likely to be settled through improvement (resolution) of simulations

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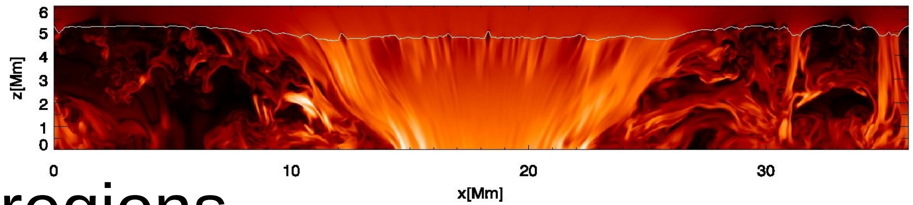
Primary uncertainty in simulation setup

- Subsurface structure and lower magnetic boundary condition
  - Vertical field @ bottom
  - No velocity in strong field regions
  - Monolithic self-similar initial field



- Ways to improvement
  - Simulate formation of sunspots
    - Challenging task, unlikely to happen soon
  - Constraints through local helioseismology
    - Combine simulations as forward modeling tool with helioseismic inversions to improve inversion and models
    - Downward extension of current simulations (~16 Mm)
    - SDO/HMI

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Prospects for an upward extension (chromosphere)

- Complicated physics (generic for chromosphere)
  - NLTE, non-equilibrium ionization (see talk by M. Carlsson)
  - Non-MHD effects (low ionization level)
  - Complicated Ohms law
  - Balance between detailed description and feasible numerical approach
  - Will need solid observational constraints to verify required simplifications (Solar C, Plan B)

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Prospects for an upward extension (chromosphere)

- Challenges of strong field region
  - Robust numerical scheme
    - High order TVD based artificial diffusivities
  - Low beta stability
    - Currently: isothermal EOS for beta < 10^{-4}
    - Future: right compromise between conservative and non-conservative treatment of energy equation
  - High Alfven velocity (> 3000 km/s)
    - Currently artificial limitation through Lorentz force reduction (saves factor 100)!
      - Problematic if study Alfven waves primary focus, in 10 years computing power sufficient for direct approach
      - Likely OK for field guided shocks (running penumbral waves, Bloomfield et al. 2007)

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Summary

- Realistic numerical simulations of sunspots feasible today
- Qualitative agreement with observations
- Not yet resolved issues
  - Presence/visibility of overturning motions
    - High resolution, 50cm telescope likely insufficient
  - Role/amplitude of Evershed flow
  - Outer penumbra, filament density
- Future directions
  - Higher resolution
  - Deeper down, subsurface structure
    - Local helioseismology, SDO/HMI
  - Further up
    - Detailed observational constraints needed (Solar C, Plan B)

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